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An Overview of Water Disinfection in Developing Countries and the Potential for Solar Thermal Water Pasteurization

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Executive Summary

This study originated within the Solar Buildings Program at the U.S. Department of Energy. Its goal is to assess the potential for solar thermal water disinfection in developing countries. In order to assess solar thermal potential, the alternatives must be clearly understood and compared. The objectives of the study are to: a) characterize the developing world disinfection needs and market; b) identify competing technologies, both traditional and emerging; c) analyze and characterize solar thermal pasteurization; d) compare technologies on cost-effectiveness and appropriateness; and e) identify research opportunities. Natural consequences of the study beyond these objectives include a broad knowledge of water disinfection problems and technologies, introduction of solar thermal pasteurization technologies to a broad audience, and general identification of disinfection opportunities for renewable technologies.

Waterborne disease is a staggering problem. Several billion people drink water potentially contaminated with pathogens that cause a variety of diseases. There are approximately 2.5 billion cases of waterborne sickness per year, causing about 5 million deaths per year (mostly children). Variables that are relevant to water disinfection problems and potential solutions include:

- Local population density: urban, village, and dispersed single family
- Existing water supply: deep-sealed well, shallow unsealed or sealed well, surface waters
- Water treatment: acceptable, questionable, or none
- Water pathogens: bacteria and viruses are ubiquitous, but protozoa and worms are localized
- Water turbidity: clean well water to "dirty" river water
- Water use: from several to several hundred liters per day per person
- Hygiene and washing practices: dependent on water supply and culture
- Availability of electricity: reliable, questionable, or none
- Local labor cost
- Income
- Infrastructure issues: varying access to supplies; training for operation, maintenance, and repair; and organizational support
- Education: implications for operation and maintenance of complex technologies
- Awareness of disease (the fecal-oral cycle): affects motivation to invest in and maintain water treatment.

Desired data are not readily available. The market segments of interest here are those with smaller volume/day demand (less than 25 m^3/day), including villages, and both dispersed and urban single family. Many authors believe that, for this market segment, the infrastructure issues are foremost in choosing the appropriate technology.

Water pathogens include bacteria, viruses, protozoa, and worms. Bacteria and viruses are readily treated with chemicals and ultraviolet (UV) light, but smaller bacteria and viruses are too small to be mechanically filtered. Protozoa and worms are larger and more easily filtered mechanically; however, they are resistant to chemicals and radiation. Turbidity in water allows viruses and bacteria to escape chemical and ultraviolet treatments. Water turbidity must be reduced by filtering to acceptable limits before chemical and ultraviolet techniques can be effective. Thus, chemical and UV treatments are almost always combined with filtering designed to reduce water turbidity to ~5 nephelometric turbidity units.

Disinfection methods appropriate for smaller-scale markets in the developing world include chlorination (dosing plant and batch processes), oxidant generation from electrolysis, slow sand filtration, household filtration, UV irradiation (from both sunlight and UV bulbs), boiling, and solar thermal pasteurization. These technologies are described, with emphasis on characterizing lesser-known solar thermal techniques. Solar

thermal pasteurization includes batch and continuous-flow devices. Commercial devices using domestic hot-water technology have recently become available. To determine if there is a potential role for solar thermal techniques, technologies are compared on the basis of economics and appropriateness.

Principal economic comparison indices are the life-cycle water treatment cost per unit volume and the capacity cost (first cost per unit volume capacity). Technology costs reported in the literature vary widely (factors of two or more). Cost estimates provided here are considered approximate averages that could vary more than a factor of two in particular cases. Appropriateness comparison is based on assessment of effectiveness and maintenance needs. Maintenance needs are broken down into need for supplies; need for skilled labor to operate, maintain, and repair the system; and need for unskilled labor for operation and maintenance.

Economic comparison of selected technologies is summarized in Figure 1. Recently emerging solar thermal pasteurization systems have a high cost compared to the village-scale technologies. On the home scale, boiling has no capacity cost, but has a very high treatment cost because of high fuel costs. Existing solar devices have a water treatment cost of an order of magnitude less than boiling.

Appropriateness comparison is difficult but critical in choosing a technology. Chlorination requires a continuing supply of fresh chemicals. Batch chlorination is very easy but only moderately effective. (Cysts, eggs, and high turbidity present problems that require filtering.) Chlorine-dosing devices in treatment plants require trained operators and increase in complexity with the size of the system. Water pretreatment with roughing filters is usually done in dosing plants. Slow sand filters are effective and low cost but require lots of maintenance and construction labor. Pretreatment with roughing filters is usually required. Household filtration units are moderately effective; however, they require consistent maintenance and are prone to failure from cracking and problems with bacteria and viruses. Batch UV sunlight methods are emerging that are very low cost and easy to use but are very small scale, moderately effective, and need further study. UV lamp techniques are moderately simple; however, high turbidity or cysts/eggs require filtering. The devices require access to infrastructure for bulb and power supply maintenance. Water boiling is common and effective but is extremely costly and laborious. Solar thermal water treatment costs are relatively high with current technology. For solar thermal pasteurization systems with metallic passageways, maintenance considerations might include scaling and freeze damage. These issues should be taken as restrictions on suitable sites, rather than as maintenance problems. Solar thermal is inherently very low in maintenance if these restrictions are followed. Solar thermal pasteurization is extremely effective against all pathogens, and does not require substantive filtering before treatment.

Solar thermal pasteurization tends to cost more than the alternatives, but is the most effective and (in some markets) requires the least maintenance. It is unclear whether appropriateness advantages will overcome cost disadvantages. Economic assessment is uncertain because solar thermal pasteurization is an emerging technology that has not yet been cost optimized to the extent that other technologies have. If costs of $380/m^2 could be attained, home-scale use would be competitive with the best home filter and UV/photovoltaic (PV) system. If costs of $90/m^2 could be achieved, village-scale application would become cost competitive with PV-driven ultraviolet techniques.

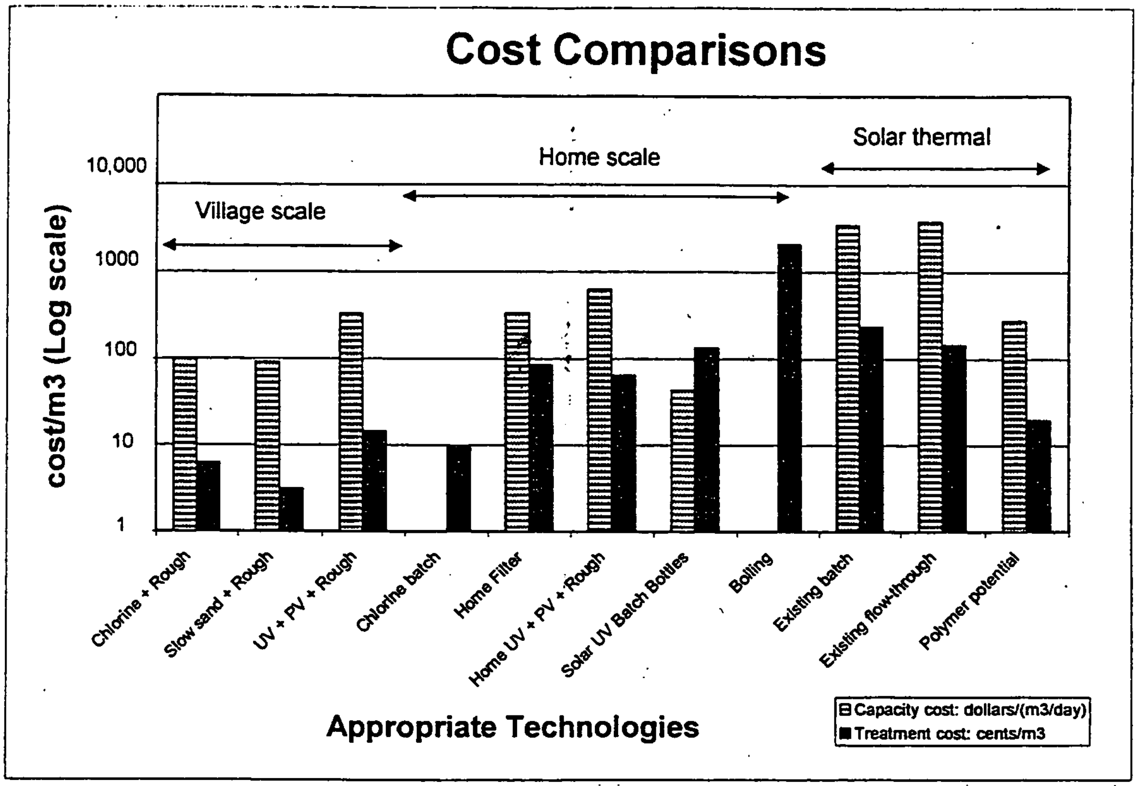

Figure 1. Cost comparison between selected small-scale water disinfection technologies. The y axis is the normalized costs on a logarithmic scale. The hatched bar is the capacity cost, which is first cost divided by the daily output of the system in $/m³. The solid bar is the normalized life-cycle cost of water disinfection in cents/m³.

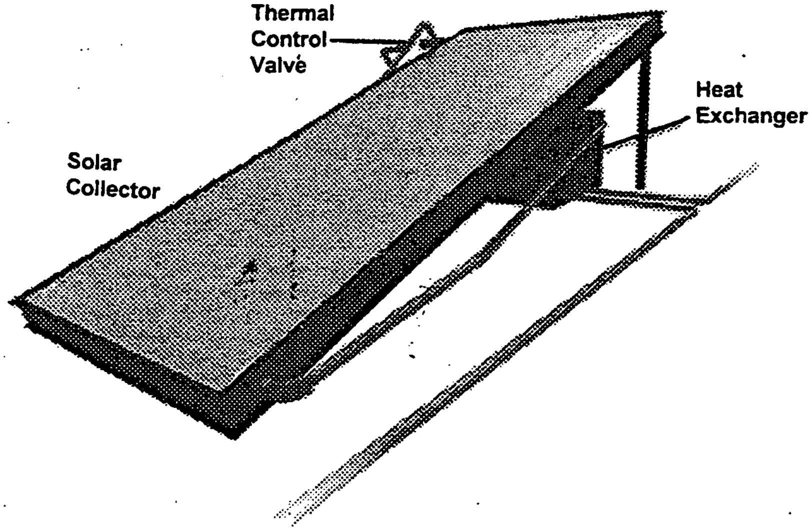

Figure 4.4.3.2-6. The Family Sol-Saver pasteurizer from Safe Water Systems (Hartzell 1997).

just released by Watts Regulator Company. The valve is driven by expansion/contraction of a wax phase-change phase-change material; at about 80°C the phase change drives the valve open. The valve has been tested without failure to 10^6 cycles. It is recommended that the seals in the valve be replaced every 10 years. A valve refurbishment kit (Viton O-ring and return spring) is supplied with the unit. A unique, ingenious, and attractive feature of the Family Sol-Saver is that it can be combined with the Wood-Saver unit (see Section 4.4.2.1) to provide a means of producing pasteurized water during cloudy/night periods. Such a device might be considered for any small-scale solar thermal device so that water supply during extended cloudy periods does not become a problem. Cost-effectiveness of the combined unit was not considered. An anti-scale magnetic conditioning device is provided with the unit. As far as we know, the effectiveness of the magnetic device has not yet been proven.

Cost

The Family Sol-Saver costs $1,650 FOB with user cost estimated at about $2,150. The combined cost of the Family Sol-Saver and Wood-Saver unit is $1,800 FOB. The cost of the heat exchanger is about $400, and the valve cost is about $100 (Hartzell 1997). It should produce about 570 L (150 gal) per day, based on five hours equivalent peak sun. Capacity cost for the Family Sol-Saver is estimated at $3,800/m^3/day and water treatment costs at $1.40/m^3.

Appropriateness

The first cost of the Family Sol-Saver is relatively high, as is the life-cycle cost of $1.40/m^3. However, the unit requires only valve maintenance, if scale and freeze damage are not concerns.

Parabolic-Trough Solar Pasteurization System

Compared to flat-plate collectors, concentrating collectors have the advantage of higher efficiency at higher operating temperatures. Sayigh (1992) studied a Fresnel reflector. A parabolic-trough system was proposed as the heat source for disinfection. A demonstration system was described by Anderson (1996) and is shown in Figure 4.4.3.2-7. It consists of a tracking parabolic trough, an inexpensive automotive radiator control valve, a patented counterflow tube and shell heat exchanger configuration compactly located beneath the absorber, and a PV-pumping system. (The pump power, pressure drops, and PV panel size were not given.) The heat exchanger configuration is shown in Figure 4.4.3.2-8, and includes wire windings to increase the film coefficient between hot and cold fluids. The inner pipe is dead space. Pumping is probably not optional because of the narrow absorber and return annuli. The effectiveness of the heat exchanger is about 67% for a single-trough configuration.

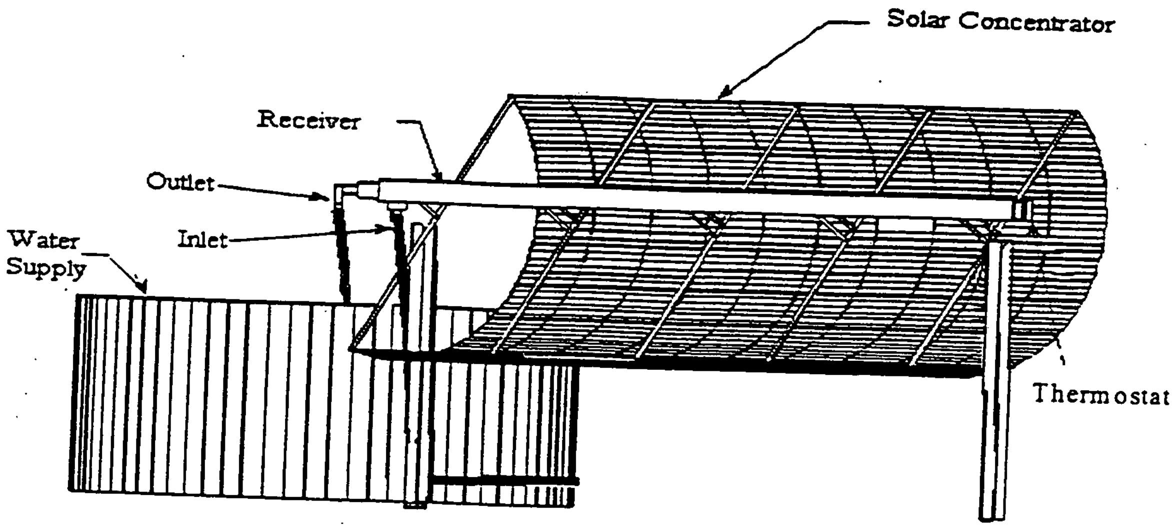

Figure 4.4.3.2-7. A parabolic-trough solar pasteurization system consisting of a tracking parabolic trough, control valve, patented counterflow tube and shell heat exchanger, and a PV-pumping system.

Cost

The trough first cost is \$250/m^2. (One trough is 6 by 2.3 m.) This is 15% below the current unit area cost for small-scale applications, because the automated controller will be omitted. The PV system was assumed to power a 40-W pump, and the sizing and costing methods in Appendix F were used for PV system costs. The heat exchanger construction is intended to be included in the estimated cost but may drive the cost higher. Maintenance is a significant issue. The reflector surface should be replaced every five years (Hale 1997) at a cost of \$50/m^2, including installation. PV system maintenance (battery replacement) was assumed to be \$25/year. There can also be maintenance issues with the flexible-piping connections on trough systems (Hale 1997). The capacity cost for a trough system is estimated at \$4,100/m^3/day and water treatment cost at \$1.74/m^3.

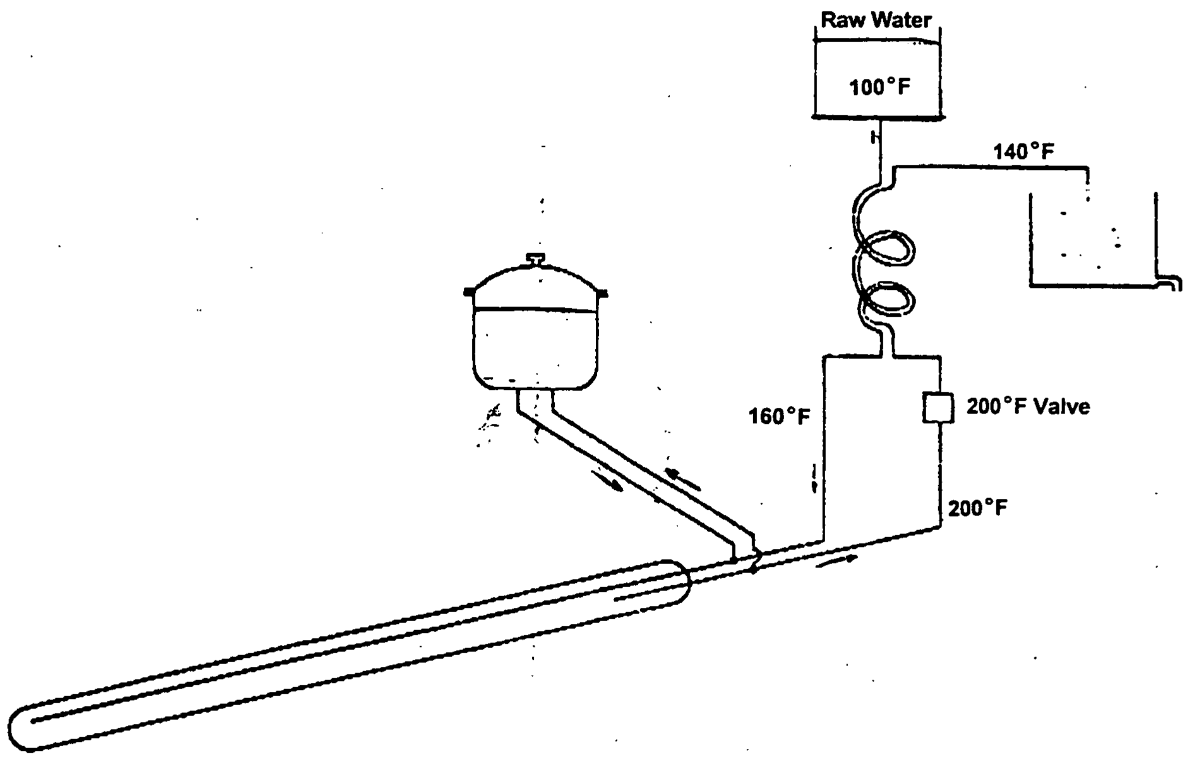

Figure 4.5.1-2. SUN multi-use system for single-family application.

4.5.2 Copper Sunsation Plus

A combined hot-water/pasteurization system is shown in Figure 4.5.2-1, with a schematic in Figure 4.5.2-2. It is in the final stages of development at Safe Water Systems, Inc. In this system, the water to be disinfected is heated until the wax-driven control valve (as described in Section 4.4.3.2.1) opens. The pasteurized water exits to a heat exchanger (a copper coil) located in the hot-water storage tank. The pasteurized water gives up a fraction of its energy before exiting. The hot water in the storage tank would presumably be used for bathing, according to the manufacturer. This would be satisfactory if cysts and worms that can penetrate the skin were not present in the water.

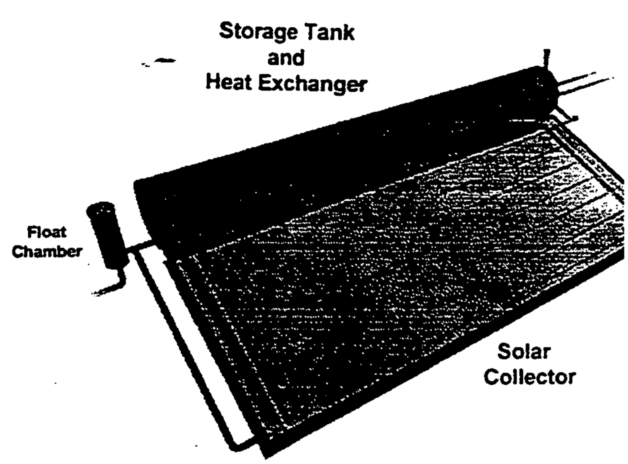

Figure 4.5.2-1. A combined hot-water/ pasteurization system. The system is in the final stages of development by Safe Water Systems, Inc.

The Copper Sunsation is projected to be available in mid-1997 and to cost about $1,350 FOB. The system should not be used in climates with chance of freezing. Like all systems having collectors with metallic passageways, scaling maintenance is required in hard-water areas.

Present flow-through solar systems cost approximately \$600/m^2, indicating good cost competitiveness with home filtering and far superior performance to boiling. However, solar water costs are high versus the larger-scale treatments and chemicals. Polymer systems may cost about \$100/m^2. These systems could compete with MOGGOD and the upper end of UV-lamp technologies, opening up the village-scale market to solar thermal technologies. The potential solar systems will not compete on cost alone with chlorination or with slow sand filters. Batch solar systems currently cost approximately \$60/m^2, competitive with home filtering and much more cost effective than boiling.

5.2 Solar Thermal Market Estimates

The potential market for solar thermal products justifies continuing research and development (R&D) in this area. Table 5.2-1 divides the market into three load strata. Within these three strata, we list potential market estimates for solar thermal systems. Although the raw potential market is huge (see Section 2.1), the practical market is considered much smaller (see Section 2.2), as summarized in the table. The maximum potential is approximately 1 million systems, mostly of the small single-family type. These estimates are highly uncertain but do provide order-of-magnitude values. Some of the considerations and numerical assumptions are discussed below.

Table 5.2-1. System Capacity/Water Volume and Markets for Solar Thermal Disinfection

Capacity Category	No. People Served	Volume (L/day)	Markets	Maximum No. of Solar Systems[4]
Small	5–50	20–200[1]	sf-1 to sf-5	1.6
Medium	10–100	100–1000[2]	v-1	0.08
Village	50–500	200–2000[3]	v-2,3	0.01

[1]Low-level single family is for drinking water/nonboiled cooking, at 4 L/person per day; high level is for drinking, hygiene, and bathing at 40 L/person per day.

[2]Health clinic water use is 10 L/person per day, drinking and hygiene.

[3]Public-tap usage at low volume is drinking only, at 4 L/person per day, and high volume at 40 L/person per day, for drinking and hygiene

[4]This column is the market size (see Section 2.2) times the estimated maximum solar penetration fraction.

5.2.1 Small-Volume System: Single Families

5.2.1.1 Urban Market (sf-1 + sf-3 Size is 5.8 Million)

The relevant market characteristics include pressurized private tap, electricity, good access to technical infrastructure, having access to resources, and willingness to pay (sf-1 especially). The competing technology options include chlorination, home filtering units, and "under-the-sink" UV-lamp units, in addition to boiling.

Batch solar pasteurizing is a good choice on the low-volume end. These units cost less today than potential small-scale UV systems or effective home filtering units. Low maintenance is important, but not as important as it is for the remaining single-family market. Storage vessels are required and solar access is an issue.

The *flow-through solar pasteurizer* might be a good choice on the higher end of volume needs. The high cost of present products relative to single-family resources seems to be an issue but may not be an impediment for

the wealthier segments. The potential exists for a very compact system (0.1 m^2). Potential polymer products may help the cost issue. Storage for hundreds of liters seems cumbersome for crowded urban areas, and again, solar access is an issue.

We conclude that solar thermal products may have some share of this market segment; however, uncertainty is increased by potential "on-demand" products that are more convenient. Projection is difficult, in part because future alternatives are unclear. Maximum market potential is about 20% of this segment, or about 1.2 million small systems.

5.2.1.2 Remote Single Family (sf-5 Size is 0.8 Million) and Peri-Urban (sf-2 Size is 1.3 Million)

Relevant market characteristics: no electricity, no pressurized water, access to technical infrastructure varies from poor (sf-5) to moderate (sf-2). Low ability to pay, low to no recognition of need for water treatment, especially sf-5. The competing technology options include chlorination and home filtering units.

Batch solar UV-A. The exposed plastic bags may be a good, low-cost option, suitable for the low-volume end, if thin-film issues can be resolved satisfactorily. The plastic bottles also appear to have the advantage of very low cost in both markets. Issues remain with performance in cloudy, windy, cold periods.

Batch solar pasteurizers appear to be a good choice, combining moderate first cost and low maintenance. Solar access and cloudy periods are issues.

Flow-through solar pasteurization. High first cost will remain a barrier because of low income, unless low-cost polymer systems are successfully developed. Low maintenance is a big advantage. Solar access and cloudy periods are issues. The potential exists for a very compact (0.1 m^2) system.

We conclude that batch solar thermal products might have a large share of this market segment. It will be very difficult to penetrate sf-5, but the peri-urban market, sf-2, can be more easily reached. For both segments, market potential is about 20%, or 0.4 million.

5.2.2 Medium-Volume System: Health Clinics (v-1 Size is 0.3 Million)

Relevant market characteristics: unpressurized water, no electricity, high motivation.

The competing technologies include chlorination, possibly an intermediate-size filtering device, and UV/PV/filtering. UV/PV/filtering appears to be a good option because no storage tanks would be needed. System maintenance in more remote areas is a crucial issue. Batch solar systems are too low in volume to be useful here.

Flow-through solar thermal. This is a good match in volume (e.g., Family Sol-Saver at 570 L/day) and effectiveness. Storage tanks would be needed. High current cost is a problem, with potential for low-cost polymer systems.

We conclude that flow-through solar thermal products may acquire modest market share, mainly because market access to technical infrastructure decreases. Assuming 25% market share, the solar thermal market is roughly 0.08 million systems. Because health clinic needs include sterilization, distilled water, cooking, and hot water, the most appealing products are solar thermal hybrid systems. Potentially, large market share might exist. However, these products are not well developed and are not considered further.

6.0 Research Recommendations

We examined water disinfection markets and technologies, with a focus on solar thermal opportunities. More R&D in solar thermal is needed to increase the attractiveness of this technology. Opportunities for other technologies are also identified. NREL teams focused on international markets for renewables should become knowledgeable on related water needs.

6.1 U.S. DOE Programs

6.1.1 Solar Buildings Program

Solar system costs should be reduced at all scales. On a small scale, existing solar batch products are already superior in cost-effectiveness to boiling and approach the high end of home filtering costs. Potential polymer systems could be more cost effective than competing home filter and home UV systems, and they are more effective. At moderate scales and above, flow-through solar costs begin competing with UV/PV/filters at around $120/m^3, and with MOGGOD at about $450/m^2. The latter cost goal can likely be reached with incremental cost-reduction activity on existing metallic products, and the former cost can possibly be achieved with polymer-based systems (see Section 4.4.3.2).

6.1.1.1 Incremental Cost-Reduction Strategy

The current industry solar-disinfection products would be aided by use of a low-cost heat exchanger designed specifically for a low Reynolds number and low pressures. For the Family Sol-Saver, for example, the tube and shell heat exchanger adds approximately $400 to the retail cost. Metal tube and shell designs are industry standards when water is pressurized. For low pressures (gravity feed), we might anticipate use of a plate-frame, thin-film heat exchanger (as in Appendix G), with a retail cost of around $50. This would decrease the Family Sol-Saver first cost by around 25%. The evacuated-tube systems offer a low collector loss coefficient and operation at lower irradiance. A flow-through system using evacuated-tube technology should be developed.

6.1.1.2 Polymer Systems

Polymer solar pasteurizers have many development issues in common with other possible polymer-based solar thermal applications (Burch 1997). A reasonable strategy views polymer water disinfection systems as being one of many similar systems that could follow from a unified research effort focused on polymer systems. It would be unwise to push a polymer-based disinfection system until polymer durability issues are satisfactorily resolved. If and when this is done, it may be reasonable to develop market applications. Also, the potential for collaborating on the development of disinfection technologies is high. Two U.S. solar thermal industry members and the EAWAG/SANDEC Center (a Swiss group) for water treatment in developing countries are investing in solar pasteurization.

6.1.1.3 Small-Scale Flow-Through Units

There are many market segments in the developing world and elsewhere that have very small-scale disinfection needs (approximately 10–20 L/day). Although very attractive batch units exist, there is potential for developing a very compact flow-through solar pasteurizer. With proper design, an approximately 0.1-m^2 system would provide about 20 L/day. A very compact, lightweight polymer product appears possible.